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SCIENTIFIC CONSIDERATIONS IN THE DESIGN OF THE MARS OBSERVER GAMMA RAY SPECTROMETER

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ABSTRACT

Cosmic ray primary and secondary particles induce characteristic gamma ray and neutron emissions from condensed bodies in our solar system. These characteristic emissions can be used to obtain qualitative and quantitative elemental analyses of planetary surfaces from orbital altitudes. Remote sensing gamma ray spectroscopy has been successfully used to obtain elemental composition of the Moon and Mars during United States Apollo 15 and 16 missions and the Soviet Luna and Mars missions. A remote sensing gamma ray and neutron spectrometer will be included aboard the United States Mars Observer Mission. If proper care is not taken in the design of the spectrometer and choice of materials in the construction of the detector system and spacecraft, the sensitivity of these remote sensing spectrometers can be greatly degraded. A discussion of these design and material selection criteria is presented.

I. INTRODUCTION

Remote sensing gamma ray spectrometers have been successfully flown on a number of USA and Soviet planetary missions. Gamma ray spectrometers flown aboard Apollos 15 and 16 were used to obtain maps of the chemical composition of a number of key elements for about 20% of the lunar surface[1,2]. A NaI(Tl) detector was used. One of the instruments scheduled to fly on the Mars Observer mission in 1992 is a gamma ray spectrometer (GRS) utilizing a high purity germanium detector, hp(Ge), and also having the capability to detect low-energy neutrons.

By detecting the gamma rays and neutrons emitted from Mars, the abundances and stratigraphy of a number of elements will be determined along with results related to Martian volatiles (H_2O and CO_2) and climate. Relatively strong gamma ray lines are made by the decay of the naturally radioactive elements (K, Th and U) and by cosmic-ray interactions (mainly the inelastic scatter or capture of neutrons)[3,4]. Many of these gamma ray lines can be used to determine elemental abundances of all major and many minor elements in the top few tens of centimeters of the Martian surface with an areal resolution of the order of the spacecraft altitude, which will be 360 km. Both the gamma rays and neutrons emitted from Mars will be sensitive indicators of the presence of hydrogen (water) in, or carbon-dioxide frost on, the Martian surface[5,6]. There are a number of sources of background that, if not either minimized or understood, would substantially degrade our ability to determine the elemental composition of a planetary surface from an analysis of the spectrum measured by a remote sensing gamma-ray spectrometer.

II. BACKGROUND COMPONENTS

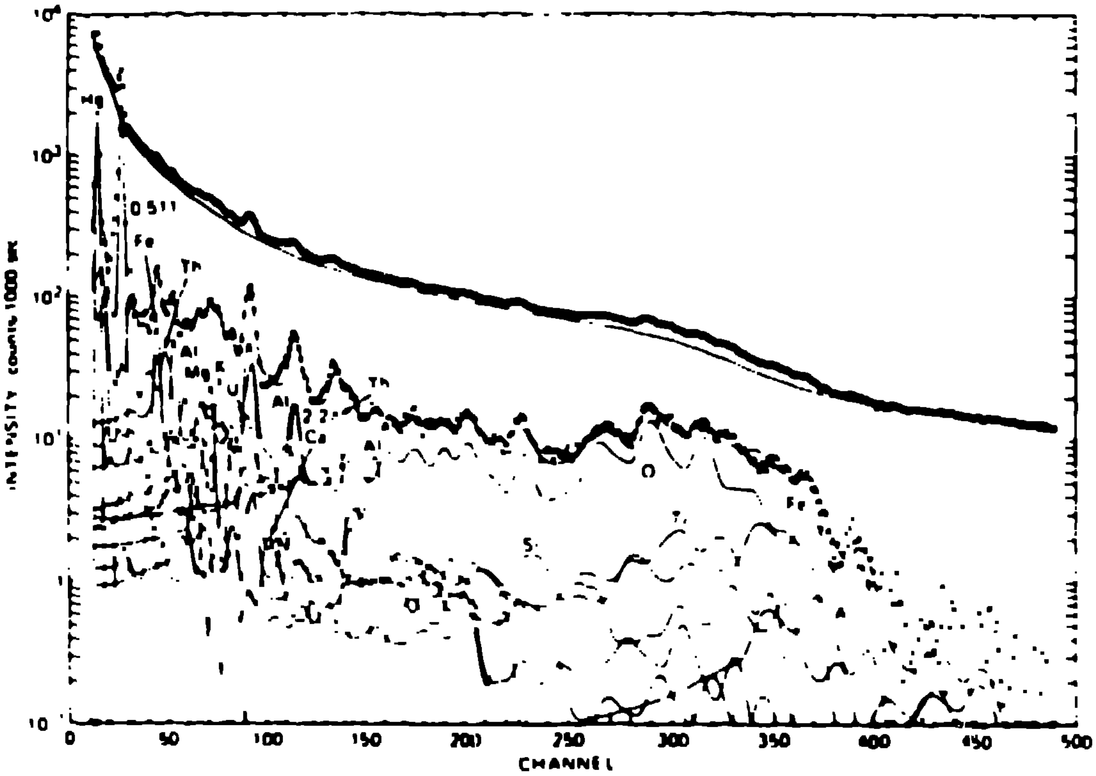
In order to illustrate the various background components, let us look at the results obtained from the analysis of the Apollo Gamma Ray Spectrometer measurements. The first major background component to be considered is that due to charged particles in the cosmic rays interacting with the gamma ray detector. Table 1 shows the ratio of the count rates in various energy intervals for gamma ray interactions to those of gamma rays plus particle interactions. An active charged particle anti-coincidence shield was used to significantly reduce if not completely eliminate the charged particle background. The basis for operation of such a shield is as follows. The gamma ray detector (high Z material) is surrounded by a plastic scintillator (low Z material). Charged particles will produce detectable interactions in both the plastic scintillator and gamma ray detector while the gamma rays will produce detectable interactions in the gamma ray detector but have a low probability of detection in the plastic scintillator. In this manner, coincidence pulse rejection is used to eliminate charged particle events in the measured gamma-ray pulse height spectrum. Thus, measurements with the shield disabled represents a mixed gamma-ray and charged particle measurement, while measurement with the shield enabled represents the comparatively pure gamma-ray component. As can be seen, the charged particle background dominates the count rate above 2 MeV.

Table 1

The ratio of gamma-ray interactions (anti-coincidence shield enabled) to that of gamma ray plus charged-particle interactions (shield disabled) as a function of energy measured during the Apollo 1[illegible] mission in orbit around the moon

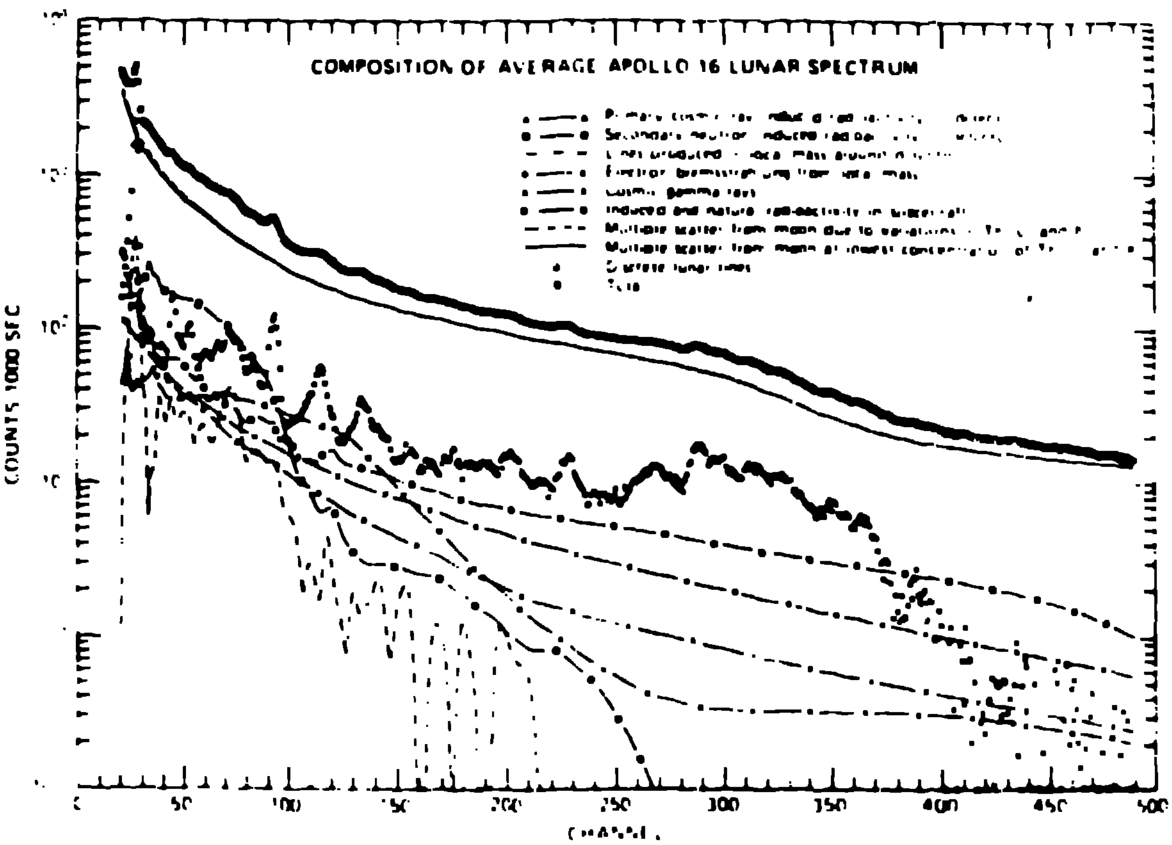
Energy MeV	Enabled ($cm^{-2}s^{-1}MeV^{-1}$)	Disabled ($cm^{-2}s^{-1}MeV^{-1}$)	Disabled / Enabled
25	3	3	1 0
1 0	18	23	1 3
2 0	08	13	1.6
5 0	0083	06	[illegible] 2
10 1	002	05	25
20 0	00075	051	68.

To illustrate the importance of the active shield, consider the gamma-ray pulse height spectrum obtained during Apollo 16, shown in Figure 1. The strongest characteristic gamma ray emission lines for such elements as O, Fe, Ti, Al are found at energies above [illegible] MeV. These lines would be much harder to detect without the use of an active charged particle anti coincidence shield



The observed pulse-height spectrum (*, top curve), the spectrum due to the continuum of photons from the Moon (top line), and the net discrete line gamma-ray pulsed height spectrum (+) obtained with the Gamma-Ray Apollo Remote Sensing spectrometer during the Apollo 16 mission and the calculated contributions (solid lines) to this epctrum by individual elelments in the moon. The energy scale is 19.3 keV/channel

Figure 2 shows the actual gamma-ray pulse height spectrum measured in lunar orbit and the background total. The various major background components are also indicated in Figure 2. The major background components shown are[1,7]:



Total gamma-ray emission pulse height spectrum (*, top points), the net lunar gamma-ray spectrum (+), and the components of the background as measured by the Apollo Gamma-Ray Remote Sensing Spectrometer in lunar orbit. The nergy scale is 19.3 keV/channe

1 Gamma-ray continuum from the surface. Since a major portion of this background component can be attributed to multiple scatter in the surface, the shape of the continuum can vary over the planetary surface, due for example to variations in concentration of the naturally radioactive species K, Th, U. This variation was seen quite distinctly on the Moon.

2 Spacecraft gamma-ray emission. These emissions can be attributed to natural radioactivity and to cosmic-ray primary, cosmic-ray secondary, and surface leakage particle induced activation. Prior to the launching of Apollos 15 and 16, detailed surveys of the spacecraft were carried out to determine its radiation cleanliness. Table 2 lists a number of sources located during the survey.

Table .

Known Radiation on Apollo 1 and 1

Radioisotope	Activity	Identification and Location
	Sources Always Present	
Potassium - 40	0.7 microcuries	EPS and ECS Radiators Thermal Paint
Potassium - 40	1.5 microcuries	KOH Electrolyte-Pyro and Re-entry Batteries
Potassium - 40	16 microcuries	KOH Electrolyte-Fuel Cells
Potassium - 40	2 1 microcuries	LM-type Battery in SM
Potassium - 40	0 003 microcuries	Mass Spectrometer Thermal Paint
Thorium - 232	5.8 microcuries	Mapping Camera Lens
Thorium - 232	microcurie range	Guidance System Heat Sinks in CM
Mercury - 203	0 1 microcuries	Gamma Ray Spectrometer
Iron - 55	1 0 microcurie	X-Ray Spectrometer
Polonium - 210	5 0 microcuries	Alpha Particle Spectrometer
	Source Jettisoned Shortly After Lift-Off	
Uranium - 238	0.1 curie	Launch Escape System Ballast Plates
	Source Jettisoned in Lunar Orbit	
Polonium - 238	1 0 microcurie	Subsatellite Particle Detector (Apollo 15 only)
	Sources on LM Descent Stage	
Plutonium - 238	$40(10)^3$ curies	Radioisotope Thermoelectric Generator on LM
Promethium - 147	200 millicuries	Landing Point Designator Paint LM
Potassium - 40	9.2 microcuries	Five Batteries

Sources on LM Ascent Stage

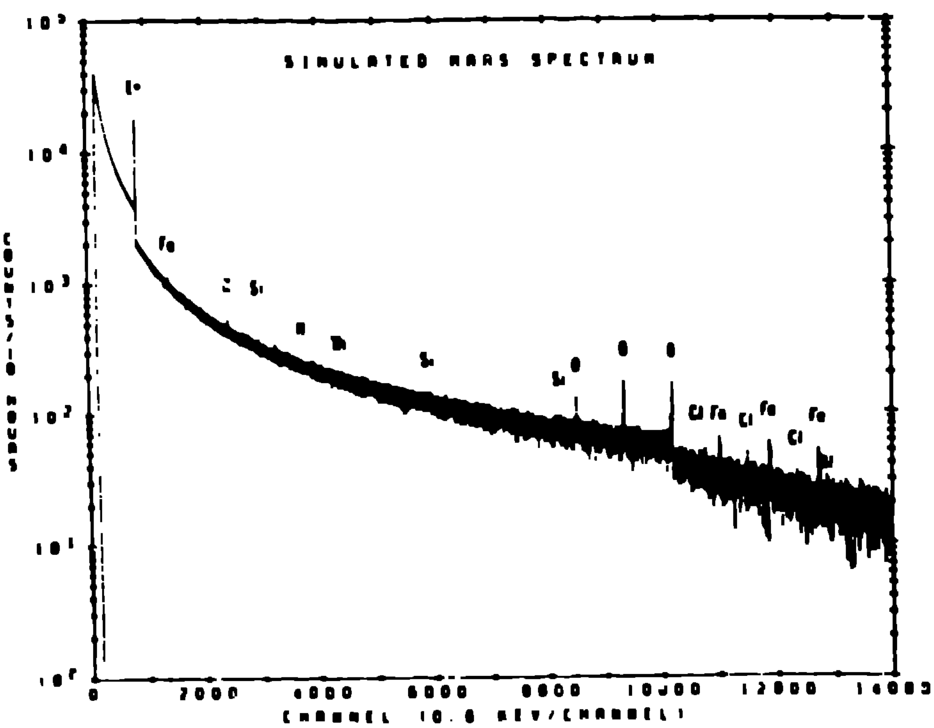
Tritium	14.[illegible] curies	Portable Life Support System
Promethium - 147	21.3 curies	Radioluminescent Discs in Lunar Module
Promethium - 147	0.2 curies	Self-Luminious Switch Tips in LM
Potassium - 40	3.7 microcuries	Two Batteries

In order to reduce the background due to gamma-ray emission from the spacecraft, the Apollo gamma-ray detector systems were placed on booms and extended away from the spacecraft. The criteria used to determine boom length (8m) on the Apollo spacecraft was to extend the detector away from the spacecraft such that the solid angle subtended by the boom and the spacecraft be at most one tenth of that subtended by the surface of the moon (at the detector). The spacecraft contribution due to cosmic-ray interaction and natural radioactivity for the lunar case was determined by measuring the gamma-ray emission as a function of distance, at intermediate and full extension of the boom during trans-lunar flight. These measurements were repeated in lunar orbit and the effects of the particle leakage from the lunar surface was thus determined.

3 Emissions from materials surrounding the detector. Contributions from the natural radioactivity and induced activity from local mass were inferred in the case of the Apollo measurements as a residual after all other components were subtracted from the pulse height spectrum. Great care was taken in constructing the Apollo gamma-ray spectrometer to reduce both naturally radioactive materials such as K-40 in the glass of phototubes and other materials that might significantly interfere with the measurement of the characteristic surface gamma-ray emission spectrum. A more comprehensive program of control has been developed for the Mars Observer Gamma Ray Spectrometer and will be discussed later

4 Gamma-ray emission from the gamma ray detector. Detector activation due to cosmic ray primary and secondary and surface leakage particles can produce both continuous and discrete line features in the measured pulse height spectra. The shapes of the background components are time dependent. This is due to the fact that the exciting flux changes with time

(e.g., trans-Mars, Mars orbit, solar flares) and the important activated species have ranges of half-lives from fractions of seconds to many years. Interaction cross-sections and detector response functions must be determined for all the component nuclear species produced must be determined, and calculational methods for predicting these background as a function of time and nature of the incident flux must be developed. Such a calculation system was developed for the Apollo program[9] and is now being extended for application to the Mars Observer Gamma Ray Spectrometer program. Accelerator experiments in both Europe and the United States have been performed to study activation in detector systems using such detector materials as NaI, CsI, hpGe, and BGO. Further studies will be carried out by the Mars Observer Gamma Ray Spectrometer Flight Investigation Team at accelerators in France and Switzerland. Emphasis will be placed on the studies of high purity Ge and BGO. Spaceflight experiments carried out on Apollo 17 and Apollo-Soyuz were used to verify the calculation system. Results of the expected response of a NaI detector in earth orbit, and the activation due to cosmic rays and the time dependence due to passing through the trapped radiation belts (i.e., the South American Anomaly)[9] are shown in Figure 3.



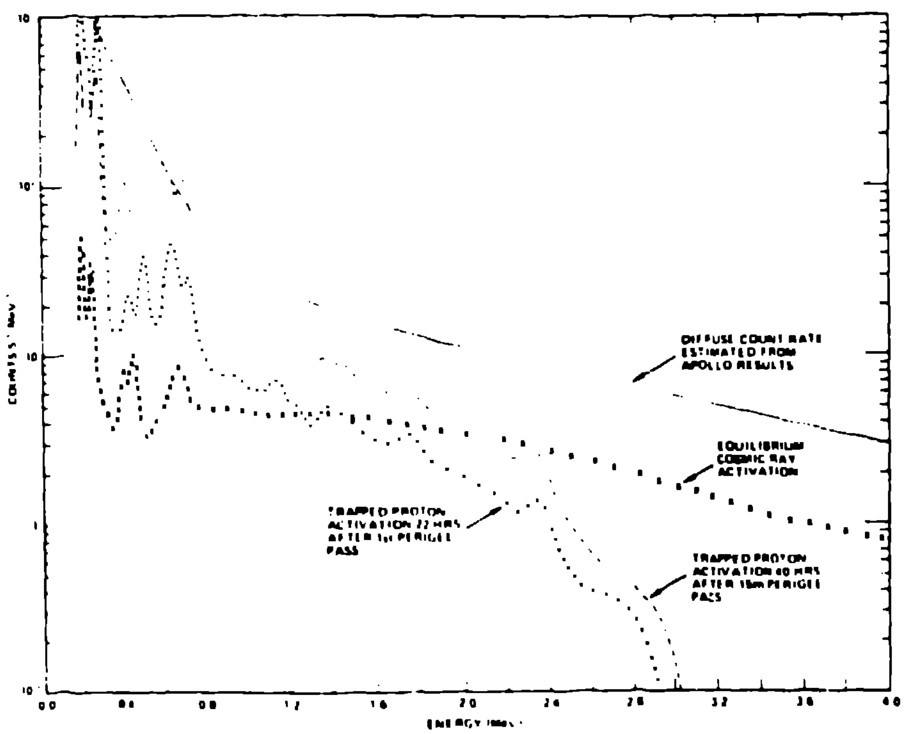
Time dependent expected response of a Na(Tl) detector in Earth orbit due to activation by cosmic ray primaries and secondaries and to trapped radiation.

5) The cosmic gamma ray background. This component is constant in time and small relative to gamma ray emission from a planetary surface. Detailed measurements of this component were carried out during the Ranger 3 and Apollo 15 and 16 missions[7,10]. The origin of this emission is still unknown. Subsequent balloon and satellite flights have confirmed the Apollo results[11].

6) Jovian electron bremsstrahlung emission. High-energy electrons interacting in the materials surrounding the detector produce a bremsstrahlung X-ray/gamma-ray spectrum. This is a continuum and is seen at all energies of interest in remote gamma ray spectrometers. This flux varies with time and space (i.e., in the solar system) and therefore becomes rather difficult to predict unless simultaneous electron measurements are made. This effect was first noticed as a difference in magnitude between the total lunar spectra measured for Apollo 15 and Apollo 16. This difference was traced to the change in magnitude of the high-energy electron flux near the Moon, which is believed to be of Jovian origin[7].

III. BACKGROUND REDUCTION PROGRAM FOR THE MARS OBSERVER GAMM RAY SPECTROMETER (GRS)

A more detailed consideration of the program for the background reduction for the Mars Observer Gamma Ray Spectrometer will be given below. All instruments on the Mars Observer spacecraft are subject to constraints in regard to money, mass, power, and data rates, thereby restricting their designs. However, an equally important constraint for the Mars Observer GRS is that the spacecraft, other instruments, and the GRS itself cause minimal interfere with the planetary gamma rays and neutrons of interest. It must be remembered that the Apollo results were obtained with a NaI(Tl) detector while the Mars Observer utilizes a hpGe detector. The Mars emission spectrum expected with a hpGe detector is shown in Figure 4[12]. The improved spectral resolution should allow us to obtain elemental analysis for more elements as compared with the Apollo system. This in a sense then further complicates the material control problem since we hope to be able to measure the abundances of many more elements. Secondly, the Mars Observer GRS will be used to obtain global elemental composition maps, thus spectra must be determined over small spatial surface elements. From the experience obtained on Apollo, it is predicted that about one half hour of data accumulation will be required over a particular surface element in order to obtain enough statistical accuracy to perform detailed elemental analyses. If one looks at orbital characteristics and considers elements near the Martian equator, this will require summing up data over about a Martian year (about two Earth years). Over this period of time, the background contribution will change. Furthermore, the Martian particle leakage spectrum will vary as a function of spatial position in Mars orbit because of chemical variation in surface composition. This is particularly affected by major changes in the hydrogen content because of soil-to-ice compositional changes. Thus it is important to minimize the background contributions where possible and be able to predict the background variation with time and orbital position.



Predicted Mars surface emission spectrum using a hpGe detector of the size being considered for the Mars Observer GRS system[12].

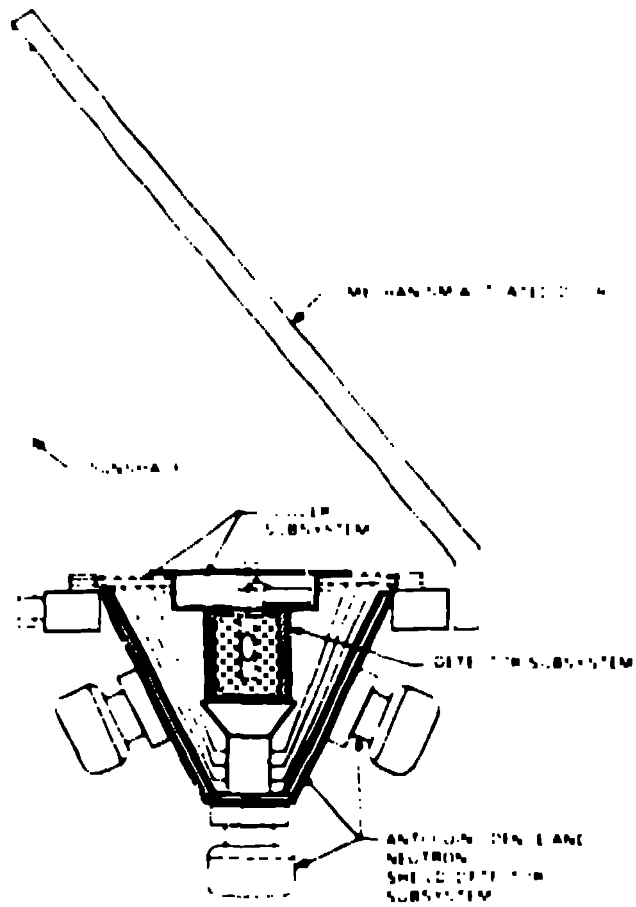
With these factors in mind we look at the Mars Observer GRS design and the plans for controlling and for understanding and predicting the various background components.

A radiation survey of the Mars Observer spacecraft will be conducted to minimize unexpected natural and artificial radioactivities, and limits of radiations from the spacecraft that reach the GRS have been included in the mission's science requirements document. It has been requested that certain elements that are excited by thermal neutrons, such as gadolinium and samarium, not be used if possible and that an inventory of such materials and their amounts and positions in the spacecraft be reported.

The GRS will be mounted on a six meter boom to reduce backgrounds from the spacecraft and other instruments. The detector is separated from the major electronics components. The electronic components are packaged in the Central Electronic Assembly (CEA). By mounting the CEA on the spacecraft the background from local matter can be further reduced.

A cross section of the Mars Observer GRS detector design is shown in Figure 5. The gamma ray detector will be hpGe cooled by a passive radiator and surrounded by a plastic anticoincidence shield to reject pulses produced in the hpGe by charged cosmic-ray particles. By including several weight percent of boron in the plastic scintillator, the anticoincidence shield can also be used to detect low energy (thermal and epithermal) neutrons[13]. The orbital velocity of the Mars Observer spacecraft, 3.4 km/s, is faster than that of a thermal neutron, so the neutron counts in the front, back, and side faces of the GRS anticoincidence shield can be used as a Doppler filter to distinguish between thermal and epithermal neutrons from Mars[13,14]. Energetic (~1 MeV) neutrons can be detected by the irregular-shaped Ge inelastic scattering peaks (which have long tails at energies higher than the inelastic gamma ray energy) that they produce in the spectra[15].

While the Mars Observer GRS Flight Investigation Team will have little control over the materials used in the spacecraft and other instruments, strong restraints have been imposed on the GRS instrument contractor relative to the materials that may be used in construction. Testing for unintentional radioactivities and elemental contamination in all materials used in the GRS construction also is being carried out. An example of this control program is presented to illustrate the approach. While beryllium would be a good choice for building the instrument (light and very few cosmic-ray induced gamma rays), the risk of radioactive contaminations in most commercially available materials, which was observed in samples of beryllium, was initially found to be too great to permit their use. Graphite epoxy is being seriously considered for some parts of the GRS structure, but we discovered an unacceptably high concentration of chlorine in epoxy samples. Chlorine may be an important element in Martian duricrust, and chlorine also produces background lines in important spectral regions. Control was then imposed on the graphite epoxy materials and chlorine-free materials are now available. Similar efforts for obtaining Be with low activity have been implemented, and it is believed that some materials may soon be commercially available.



Cross section view of the preliminary design of the Mars Observer GRS

An attempt has been made to limit in the GRS the amounts of almost all elements of interest in the Martian surface to levels that produce less background than that coming from the spacecraft or from the Martian surface. In order to quantify this effect of various chemical elements' gamma-ray emission as a function of position relative to the GRS detector, tables of acceptable mass divided by the square of the distance of that material from the hpge detector have been compiled for several key elements. (Table 3) These limits were derived by calculating the expected gamma ray flux at the detector for a number of important geochemical components in the Martian surface and comparing these fluxes with those expected from detector or spacecraft construction materials.

Table 3 Elements of Scientific Interest Permitted Near Detector

The following table gives the amount of each element of scientific interest that may be used in the vicinity of the detector without significant impact to the science. The limit is expressed as a function of mass of the element (in grams) divided by the square of the distance (in centimeters) from the element to the center of the GRS gamma-ray detector.

ELEMENT	m/r^2 LIMIT (g/cm^2)	ELEMENT	m/r^2 LIMIT (g/cm^2)
C	19.4	Mn	0.01
N	0.21	Fe	0.08
Na	0.09	Ni	0.0025
Mg	0.05	Cd	3.2 E-5
Al	0.61	La	0.00016
Si	0.31	Sm	3.0 E-5
S	0.09	Gd	2.3 E-6
Cl	0.003	Lu	7.0 E-7
K	0.0008	Th	5.0 E-7
Ca	0.06	U	3.0 E-8
Cr	0.014		

These tables indicate which materials in the GRS would contribute most significantly to our backgrounds. One of the most important scientific considerations to date was the decision whether to choose aluminum or titanium for the the Ge crystal housing and for other structural materials in the GRS instrument. It was decided that aluminum was a more desirable element to detect in the Martian surface than was titanium. Aluminum is a major rock-forming element whose abundance must be known to calculate absolute abundances of other elements. Moreover, it is a diagnostic element for the presence of aluminosilicates, such as feldspars, that could be important components of the ancient Martian cratered highlands. Thus it was decided that the GRS instrument would be built with titanium and graphite epoxy instead of aluminum.

Finally, accelerator tests are being planned to study detector and material activation problems. Studies using accelerators with protons of both [illegible] GeV and 600 MeV energies are planned for the next few years. Further programs for predicting the induced activity in space are under development. Many of these programs are extensions of those programs that were developed for the analysis of the Apollo remote sensing gamma-ray spectrometer data.[16]

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Figures

Fig. 1 The observed pulse-height spectrum (*, top curve), the spectrum due to the continuum of photons from the Moon (top line), and the net discrete line gamma-ray pulsed height spectrum (+) obtained with the Gamma-Ray Apollo Remote Sensing spectrometer during the Apollo 16 mission and the calculated contributions (solid lines) to this spectrum by individual elements in the moon. The energy scale is 19.3 keV/channel.

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